

INVESTIGATIONS OF SBS AND LASER GAIN COMPETITION IN HIGH-POWER PHASE MODULATED FIBER AMPLIFIERS (POSTPRINT)

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14. ABSTRACT Power scaling of single-frequency high power optical fiber lasers is limited due to the stimulated-Brillouin scattering (SBS). Towards that end, line broadening through white noise phase modulation can be used to suppress SBS. Theoretical models predict the SBS threshold enhancement factor as a function of linewidth and fiber length, but have yet to be experimentally verified. A radio frequency (RF) white noise source (WNS), in conjunction with RF low pass filters, is used to randomly modulate an optical signal through an electro-optic modulator (EOM). The optical signal is broadened, with optical bandwidth controlled through RF filtering. Subsequently, this modulated signal is used in a cutback experiment with a passive fiber. Studies describing enhancement factors as a function of linewidth and fiber length are investigated. Results indicate a reduction in the SBS threshold enhancement factor at shorter fiber lengths, which is in reasonable agreement with the theoretical predictions. Finally, we compare these results with cutback experiments conducted using phase modulation through pseudo random bit sequence (PRBS).					
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Investigations of SBS and Laser Gain Competition in High-Power Phase Modulated Fiber Amplifiers

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ABSTRACT

We present experimental results of SBS suppression in high power, monolithic, Yb-doped fiber amplifiers via phase modulated laser gain competition. To narrow the linewidth, two-tone laser gain competition between broad (1036 nm) and narrow linewidth (1064 nm) laser signals is investigated in conjunction with phase modulation and yields pump limited output powers of 600 W. Here integration of both two-tone and pseudo random bit sequence (PRBS) phase modulation concepts, generated SBS enhancement factors of greater than 17x at a modulation frequency of 500 MHz, without reaching the SBS threshold. Significantly, the results represent a near order of magnitude reduction in linewidth over current high-power, monolithic, Yb-doped fiber amplifiers.

Keywords: stimulated Brillouin scattering, Yb-doped fiber lasers, phase modulation

1. INTRODUCTION

High power fiber amplifiers are primarily limited by the onset of detrimental nonlinear effects, such as stimulated Brillouin scattering (SBS). SBS is a third-order phase-matched nonlinear interaction that couples acoustic phonons to photons of the optical field and the associated backscattered Stokes light. Consequently, optical power is transferred from the laser field and into the backward Stokes light; thus degrading amplification of the signal light and possibly damaging the fiber amplifier through pulsation. As such, high power (>500 W), monolithic fiber amplifiers currently exhibit linewidths greater than 10 GHz [1,2]. Typical SBS mitigation schemes include utilization of large mode area (LMA) fibers coiled to filter out higher order modes [3]. However, in order to maintain single-mode (diffraction limited) operation, conventional step-index fiber core diameters are generally limited to less than 25 μm . Another fundamental SBS suppression technique revolves around spectral linewidth broadening through radio frequency (RF) phase modulation. Generally, linewidth broadening is achieved through a filtered microwave white noise source (WNS). WNS modulation creates a continuum spectrum around the carrier with optical linewidth control provided by the RF filter. Through this approach kilowatt class, monolithic fiber amplifiers have been attained at 10-20 GHz linewidths [1]. Such large linewidths may hinder efficient beam combining, due to added path length complexities in coherent beam combining (CBC), where the coherence length is inversely proportional to the laser linewidth. Moreover, in spectral beam combining (SBC) broader linewidths may reduce the number of channels that can be combined within the Yb gain spectrum and lead to beam quality degradation (SBC) [4].

Towards that end, we report results of a pump-limited 600 W, sub-GHz linewidth, monolithic, Yb-doped fiber amplifier. The superior SBS suppression is based on two-tone laser gain competition (LGC) between a combination of broad and narrow linewidth laser signals. By seeding with appropriate wavelengths and seed powers, the effective length of the amplifier is shortened as the narrow linewidth signal experiences a rapid rise at the output end of the fiber. Since the SBS threshold is proportional to the fiber amplifier effective length, considerable SBS suppression can be attained. We have previously implemented two-tone LGC to attain a 203 W single-frequency, monolithic, co-pumped fiber amplifier [5]. Moreover, the two-tone concept has been theoretically and experimentally shown to

provide a 2x-3x enhancement in SBS threshold over single-tone fiber amplifiers. In this work, we extend the two-tone concept to higher powers using a narrow line (phase modulated) 1064 nm seed in conjunction with a broadband 1036 nm seed source.

2. PHASE MODULATED LASER GAIN COMPETITION

Recently, we have presented a theoretical study of transient SBS in optical fibers seeded with phase modulated light [6]. SBS suppression via phase modulation is examined in the time domain using a triply coupled set of partial differential equations. These equations describe a nonlinear three-wave interaction of two optical fields and an acoustic field with SBS initiated from noise. Accordingly, initial experimental validation of our nonlinear time-dependent model has been conducted for sinusoidal [7] and PRBS phase modulation [8]. PRBS, or pseudo noise, allows you to generate repeatable noise of known spectrum and amplitude, with adjustable linewidth. In contrast to the continuum spectra generated by a WNS, PRBS modulation exhibits a periodic and discrete optical frequency comb.

A PRBS pattern is typically denoted as $2^n - 1$. The power (n) indicates the shift register length used to create the pattern. The $2^n - 1$ pattern contains every possible combination of n number of binary bits, except the null pattern. Subsequently, a sinc^2 spectral linewidth is generated, with the spectral nulls occurring at the bit or clock rate. Within the sinc^2 envelope, the PRBS data pattern defines a discrete frequency comb. Here the frequency comb separation is given as $\Delta f = 1/nT$. The full width at half maximum (FWHM) of this spectrum is approximately equal to the clock rate ($1/T$) or modulation frequency. Thus, using PRBS modulation the SBS spectrum can be preferentially altered through appropriate bit rate and pattern length adjustments. Notably, through PRBS phase modulation we have attained a 1 kW monolithic (all-fiber) amplifier at 6 GHz modulation frequency and 2^6-1 PRBS pattern [8].

For laser gain competition, the seed wavelengths are sufficiently separated to avoid four-wave mixing effects with the broadband laser operating near the shorter end of Yb gain spectrum (~ 1035 nm) and the single-frequency (or narrow linewidth) laser operating at the longer wavelength (1064 nm) end. Furthermore, sufficient separation in wavelength is required for the broadband signal to efficiently induce core pumping of the single-frequency signal. Based on the spectroscopic properties of Yb-doped fibers, the laser gain factor at 1064 nm is larger than at 1035 nm in the two-tone amplifier. At the input end of the fiber, sufficient 976 nm pump power is present to induce amplification in both signals. As the signals and pump propagate along the fiber, population inversion will decrease, leading to absorption of the shorter wavelength light and transfer of its energy into the longer wavelength signal. As such, optimal two-tone seeding ratios are critical towards increasing the SBS threshold. To achieve significant buildup in the power of the shorter wavelength signal prior to the transfer of its power to the longer wavelength light, much higher seeding of the former is required.

Specifically, simulations indicate seeding ratios of greater than 10:1 are required to exceed a factor of 2 in SBS suppression; while maintaining near optimal amplifier pump efficiency in the desired single-frequency or narrow linewidth signal. We note that ideal laser gain competition seed ratios change depending on the specific two-tone amplifier configuration such as absorption, fiber type or length, and wavelengths used. Furthermore, we can extend the two-tone concept to higher powers by applying phase modulation to the longer wavelength light; leading to multiplicative SBS suppression.

The experimental setup of our monolithic, two-tone fiber amplifier is shown Figure 1. Here a 20 W broadband 1036 nm amplifier was co-seeded with a narrow linewidth (phase modulated) 1064 nm pre-amplifier. The narrow line and broadband signals were then combined through a wavelength division multiplexer (WDM) from Laser Zentrum Hannover. The combined signal was then fusion spliced onto a high-power (6+1)x1 tapered fiber bundle (TFB) pump combiner from ITF Labs. Next, the TFB output was spliced to the final high power gain stage consisting of Nufern non-PM 25/400 μm gain fiber. In addition, a 1% tap coupler was inserted to monitor the forward and

backward propagating light. In order to characterize the SBS response, the backward tap was spliced onto a 50/50 splitter to allow us to simultaneously monitor the power of the backward light on a photodiode and its spectral content on a 0.01 nm resolution bandwidth optical spectrum analyzer (OSA). Backward power measurements are a standard metric for SBS characterization in fiber amplifiers. Experimentally, we have found a reflectivity of 0.05-0.1% to be characteristic of operation near SBS threshold. The fiber amplifier was terminated with an endcap to reduce intensities at the output glass/air interface. At the fiber output, two dichroic mirrors were used to isolate the narrow linewidth 1064 nm signal and separate and measure the unused 976 nm pump light and unabsorbed 1036 nm broadband seed.

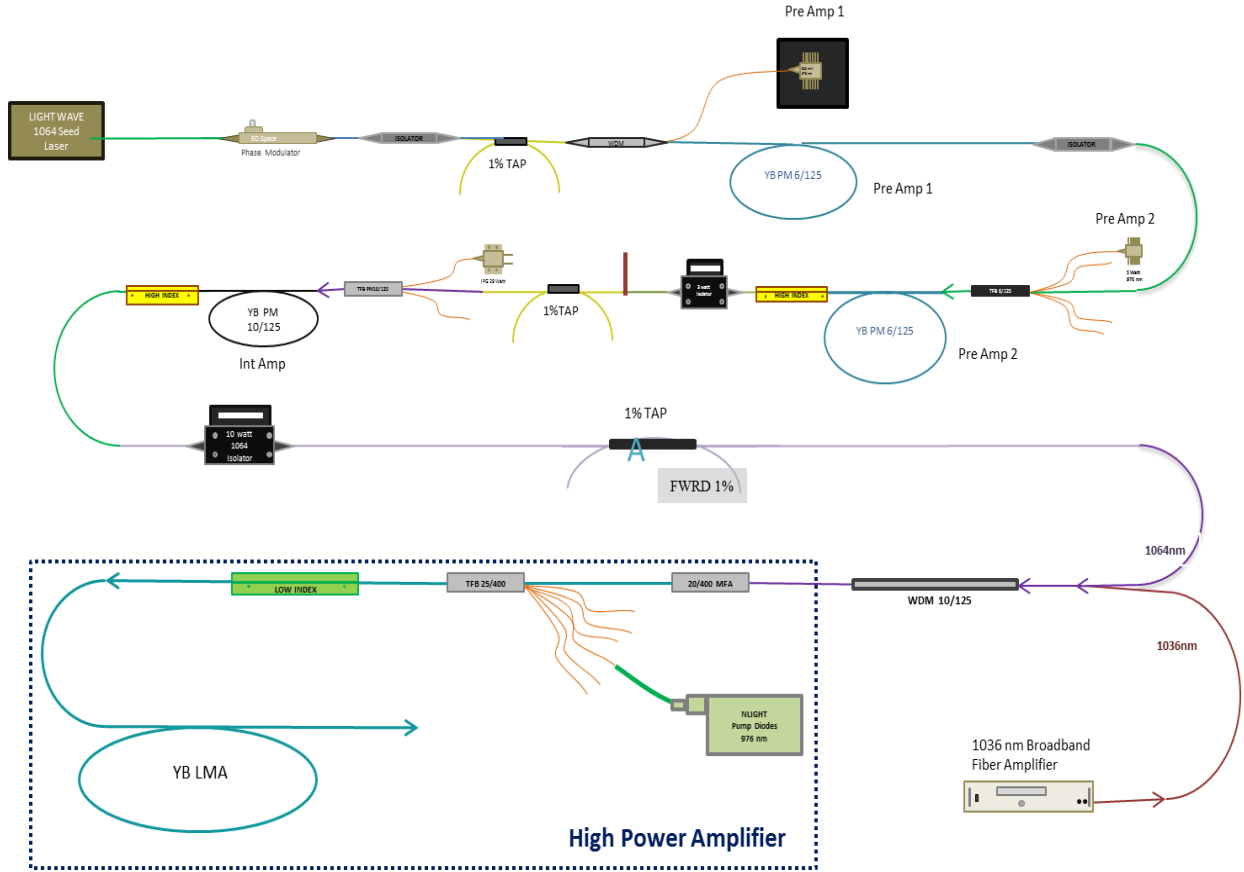


Figure 1. Experimental setup for phase modulated, monolithic, fiber amplifier with two-tone laser gain competition.

Through integration of both two-tone and PRBS techniques, SBS enhancement factors of greater than 17x were achieved at a modulation frequency of 500 MHz. The SBS enhancement factor is defined as the increase in SBS threshold over a corresponding single-frequency amplifier. Experimental power scaling results depicting backward power versus signal power for our co-pumped, monolithic fiber amplifiers are presented in Figure 2. Here we observe an SBS threshold of 35 W for the single-frequency, single-tone (1064 nm) case. Next, with single-tone seeding, we apply a 2^4-1 PRBS pattern at a phase modulation frequency of 500 MHz, and attain an SBS threshold of 240 W or SBS enhancement of $\sim 7x$. Finally, we apply two-tone LGC with a 14:1 (1036nm:1064nm) seeding ratio to achieve further power scaling. Through simultaneous application of both SBS mitigation schemes an output power of 500 W was attained without reaching the SBS threshold. We note that the backward power is still linear with respect to the forward power, indicating that the SBS threshold has not been reached.

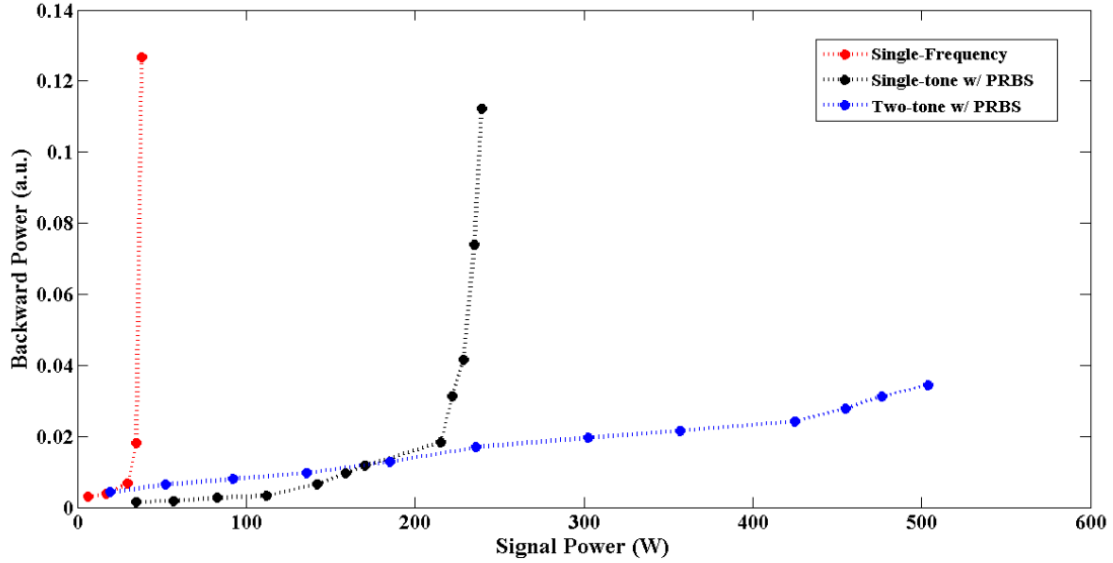


Figure 2. Measured backward power versus signal power for our high power, monolithic fiber amplifier. Plots depict a single-frequency, single-tone SBS threshold of 35 W (red curve). Next, PRBS phase modulation at 500 MHz was applied to increase the SBS threshold to ~240 W with a single 1064 nm tone (blue curve). Finally, two-tone LGC with 1036 nm and 1064 nm seeds was applied resulting in a pump-limited output power of 500 W, at a modulation linewidth of 500 MHz.

Ideal seeding ratios between the 1036nm and 1064nm seed sources leading to optimal SBS suppression were investigated. As mentioned, appropriate seeding ratios are required to induce efficient LGC pump energy transfer. Consequently, seeding ratio optimization yielded a 600 W, 500 MHz, pump-limited monolithic fiber amplifier. Plots of the launched pump power versus output power (black) and backward reflectivity (blue) are shown in Figure 3. Here a 19:1 (1036nm:1064nm) ratio was implemented and optical pump efficiency of 80% was achieved. We also conducted beam quality measurements using a Spiricon M^2 beam analyzer. A plot of the beam profile at 600 W is shown in Figure 4, with the corresponding laser beam profile shown in the inset. An M^2 value of ~1.2 was measured, indicating near-diffraction limited operation.

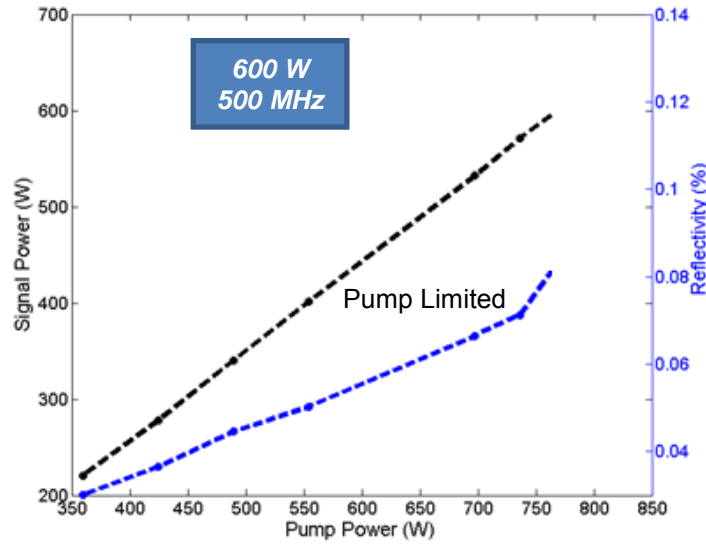


Figure 3. Pump-limited 600 W, 500 MHz, monolithic fiber amplifier with ~80% optical efficiency.

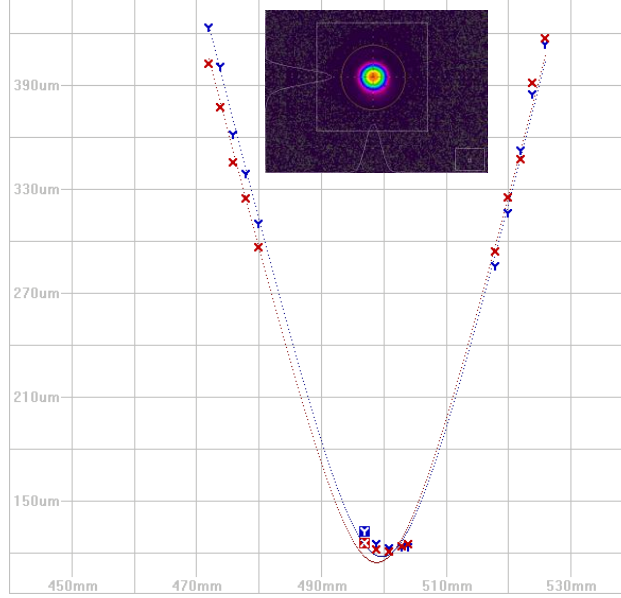


Figure 4. M^2 beam quality measurement of our monolithic, fiber amplifier at 600 W. Notably, excellent beam quality was attained with an M^2 of 1.2. Inset shows laser beam profile.

3. CONCLUSION

We have conducted experimental investigations of SBS suppression in narrow linewidth high power, monolithic fiber amplifiers seeded with two-tone laser gain competition. To narrow the linewidth, laser gain competition was implemented in conjunction with PRBS phase modulation, yielding a 600 W monolithic fiber amplifier at a sub-GHz modulation frequency of 500 MHz. Significantly, the results represent a near order of magnitude reduction in both SBS and laser linewidth over current state of the art high power, monolithic, Yb doped fiber amplifiers. Moreover, the pump-limited results were attained without the onset of SBS. We expect that further power scaling at a modulation frequency of 500 MHz should yield an SBS threshold of ~ 700 W; in accordance with the laser gain competition 2x-3x SBS threshold enhancement. More importantly, the promising results allude to the possibility of monolithic, sub-GHz, kilowatt-class Yb doped fiber amplifiers.

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